# Advantages in using Thermal Integrity Profiling

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## ABSTRACT

There are several different integrity test methods available for assessing drilled shafts/bored piles, ACIP/CFA piles, and diaphragm walls and panels. Each of these test methods offers both advantages as well as limitations for the applications. Many times, the integrity method is chosen without a great deal of understanding on what the test can truly indicate and equally important, what the test method is unable to highlight. This paper will outline the various test methods along with the advantages and limitations for each and will focus on the capabilities and advantages of using Thermal Integrity Profiling as the primary deep foundation integrity testing method. As the Thermal Integrity Profiling method is deployed widely throughout the world, it is important to understand the method and all the capabilities and limitations. The Thermal Integrity Profiling method will be explained in detail along with case histories where Thermal Integrity Profiling was implemented.

**Keywords:** Integrity, Thermal, Testing

## INTRODUCTION

Integrity testing is an integral part of any successful cast-in-place foundation project. Generally, with cast-in-place foundations it is difficult to impossible to inspect the elements prior to completion. There are several different methods available to test these cast-in-place foundations for integrity. Each of these methods has advantages and limitations.

The most basic test method available for cast-in-place foundations is the Low Strain Integrity test. The Low Strain Method uses a highly sensitive accelerometer fixed to the pile top with a seating compound. The pile top is struck with a handheld hammer inducing a compressive wave into the element. The compressive wave will reflect back to the surface from any change in pile impedance or diameter or ideally, from the pile toe. This method can be used on most newly constructed/cured cast-in-place foundations with no preplanning required. This is a major advantage to this test method. Additionally, it is typically quite simple to test many or even all foundation elements on a project, given sufficient planning. Although the Low Strain Integrity testing method is generally quite cost effective, this method has several major limitations. Among these limitations are the limited ability to assess embedded lengths that exceed approximately 30 times the pile diameter, the limited ability to fully assess the concrete in the upper diameter, the unknown wave speed which can give inaccuracies in the analysis of the lower portion of the pile, and the inability to get an identifiable toe reflection when the piles are installed in strong soils or seated in rock. The method also has difficulties when piles are irregularly shaped, particularly near the top, causing multiple reflections which may mask anomalies within the embedded length. The disadvantages generally limit the use of Low Strain testing in many parts of the world to a secondary or confirmatory test used in conjunction with other more sophisticated methods.

The Cross-Hole Sonic Logging (CSL) method is a non-destructive test method widely used throughout the world. With the CSL test, bored piles need to have access tubes installed during construction for the test to be possible. The tubes are generally 50mm diameter and made of steel. Steel tubes are preferred over PVC tubes as the thermal coefficient of expansion for steel and concrete are similar while the thermal coefficient for PVC is approximately 4 times greater than that of concrete. This inequality in expansion and contraction rates between concrete and PVC can cause tubes to de-bond from the concrete leaving small air gaps around the access tubes, resulting in signal generation loss, with the upper portion of the tubes typically being most affected. The CSL access tubes are installed at a frequency of one tube per 300mm of pile diameter, equally spaced around the pile and tied to the reinforcing cage. Prior to casting, the access tubes are filled with freshwater to suppress buoyancy effects and aid bonding between steel and concrete. Once sufficient curing of the concrete has occurred, approximately 7 days after casting, the CSL test can be performed.

The CSL test is performed by lowering the transmitter/receiver probes to the bottom of the access tubes. The probes are slowly raised while transmitters radiate an ultrasonic pulse with a frequency of approximately 50 KHz. The depth of each probe is tracked via individual encoders placed on the top of the access tubes or nearby on the surface. The receiver probes receive this ultrasonic transmission. The pulses occur at regular depth interval along the entire length of the pile until the probes have reached the surface. It is important to keep the probes close to the same height within the pile throughout the test to ensure optimum accuracy in the analysis. The process is repeated until all profiles have been scanned for the pile under test. Knowing the separation between the CSL access tubes and the time for the transmission to travel from transmitter to receiver, the apparent wave speed for each data transmission set is obtained.

An anomaly can be detected if it is present in any of the direct transmission paths as it will show up as a localized delay in arrival time/decrease in wave speed. Additionally, a localized decrease in the relative energy of the received signal can be an additional indicator of an anomaly within the direct transmission path. Both parameters are used when assessing acceptance criteria.

The CSL test has the advantage of being able to scan the full length of the pile, provided the access tubes extend to the bottom of the pile. Additionally, with an even number of access tubes, the CSL test can reveal the depth and quadrant the anomaly is located. The CSL test can reliably detect an anomaly in the direct transmission path but cannot assess the area outside of the reinforcing cage or areas not within the direct transmission path. Additional significant limitations of the CSL test include, the susceptibility for de-bonding and bleed water channels, the limited cross-section assessed in a typical test (60% at best), small anomalies very near the access tubes appearing as large anomalies, and the impractical nature on the use of CSL for CFA type piles. There is an additional safety concern with installation of CSL access tubes for use in applications where a segmental cage is use and the splicing occurs in the excavation. During the time when the cage sections are being spliced, site personnel are working for extended times with their hands and arms inside a cage which is suspended above the excavation. If these cage sections should slip for any reason, great harm can come to individuals who are working with hands and arms inside the cage. This safety concern is a considerable risk for any project where spliced cages are being used. Additionally, there are many applications where the space requirements don’t allow for the placement of CSL access tubes such as in panels where there is often limited space for CSL access tubes as well as bored piles used for electric transmission lines where the mounting bolt template severely restricts the space needed for CSL access tubes making this an impractical method for these applications.

Although both the Low Strain and CSL methods are widely used and have meaningful advantages, there are limitations in each method that don’t allow for either method to provide a complete view of the pile cross-section over the entire length. These limitations can be overcome with the Thermal Integrity Profiling test method.

## THERMAL INTEGRITY PROFILE BACKGROUND

The Thermal Integrity Profiling (TIP) method measures the elevated heat during the hydration process of concrete to assess the integrity of cast-in-place foundations along their entire length and cross-section. Embedded thermal sensors placed directly into the concrete for bored/CFA piles and wall panels make the temperature measurements. The Thermal Wire® cables are tied to the reinforcing cage at a frequency of, in the case of piles, one wire per 305 mm of pile diameter (a 2m diameter pile would have 6 thermal wire cables installed), equally spacing the wires around the pile. It is recommended that an even number of wires be installed, with pairs being placed diametrically opposite one another to enable lateral movement, if any, of the reinforcing cage to be easily determined. These Thermal Wire cables have temperature sensors placed every 300mm vertically along the length of the cable. In the case of diaphragm wall panels, spacing is usually kept to 1m to ensure sufficient overlap and coverage. For a mini type pile or CFA pile with a single center bar and no reinforcing cage, a single Thermal Wire cable can be attached to the central bar. When cages are assembled in sections above the excavation, Thermal Wire cables will have an underwater quick connector integrated into the wires to allow the two wire sections to be connected by simply pressing together the underwater connector. This connection is made in minutes and can be done outside of the reinforcing cage, minimizing the risk of serious injury to site personnel during this process. In all scenarios, once the concrete has been placed in the shaft, the Thermal Wire cable(s) are connected to special purpose data loggers. The data loggers automatically read each node along the associated wire at regular time intervals of typically 15 minutes. These readings are typically viewed “live” via the “cloud” based software on a regular basis, allowing the data acquisition to proceed with no site visits required from the specialist testing agency. The data loggers remain connected to the Thermal Wire cables from time of concrete placement until the concrete in the pile has reached its peak temperature. Because the Thermal Integrity Profiling test is completed during the early portion of the hydration process, up until the pile reaches peak temperature, which is typically within 48 hours of casting, the analysis will be done very early in time allowing for an accelerated construction schedule, unlike the traditional methods described earlier.

The Thermal Integrity Profiling (TIP) method creates a series of temperature vs. depth plots as a function of time. The plots are typically shown with temperature on the horizontal axis and depth on the vertical axis. The heat transfer away from the shaft is radial along the length of the shaft. However, within the top and bottom one diameter of the pile the heat transfer is both radial and longitudinal and thus the temperatures profiles show a roll-off in these zones. This temperature roll-off at the top and bottom of pile is typically seen in a temperature vs. depth plot and has a hyperbolic tangent shape. Knowing that the top and bottom roll-offs have a predictable shape allows for an adjustment to the temperature measurements at the top and bottom of the pile. When the hyperbolic tangent function is applied to the shaft top and bottom roll-off, the roll off portions of the adjusted curve then match the theoretical interior measurements, with the temperature curve generally flattening out in the upper and lower roll-off regions. Once the top and bottom of the temperature curves have been adjusted, a consistent analysis can be performed for all temperature measurement locations within the pile.

The temperature measurements are directly related to the cement content, concrete volume, and concrete quality. The temperature sensors are reading the localized temperature and are affected by any deviations in the surrounding area of the sensors, including the area outside the reinforcing cage. This ability to assess both inside and outside the reinforcing cage allows for 100% of the cross-section to be evaluated via the Thermal Integrity Profiling (TIP) method. If we have a localized and abrupt temperature reduction, this indicates a localized anomaly. Conversely, if we have a localized increase in temperature this would indicate a localized bulge. At each depth all temperature readings are averaged together to determine the overall shape of the pile as a function of depth. If an anomaly should occur, the optimum time to evaluate the extent of this anomaly would be half the time from completion of concrete placement to peak temperature.

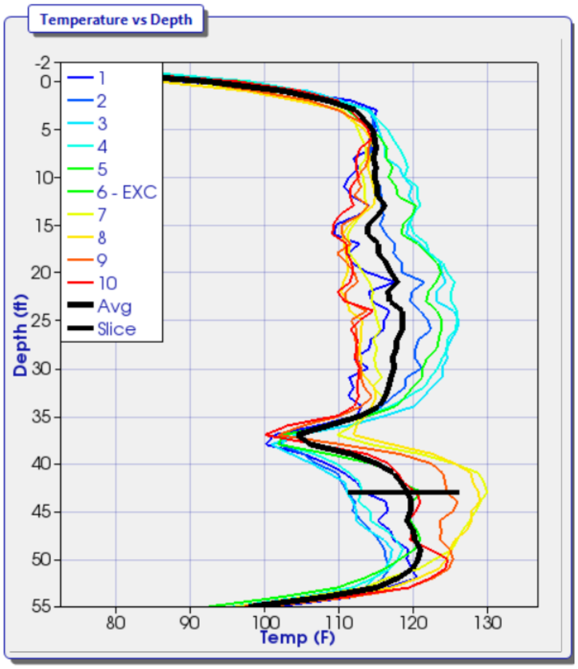


Figure 1 Localized anomaly in the pile.

The example shown in Figure 1 has temperature measurements for a large diameter pile which has an abrupt temperature reduction at a depth of approximately 11m (36 feet). The thermal data indicates a significant anomaly that can be seen in all individual wires at this depth. The thermal data further indicates that the anomaly is greatest in the regions located between wires 1 through 6 and wires 9 and 10. The region nearest to wires 7 and 8 has less of an abrupt temperature change indicating this zone has a smaller anomaly than in the remainder of the cross section at this depth. If coring were to be done, to examine an anomaly, it would be recommended that it be done in the region where the anomaly is greatest.

In addition to determining concrete integrity, the Thermal Integrity Profiling (TIP) test will also reveal reinforcing cage eccentricities by comparing measurements from radially opposite locations versus the average value at the same depth. If a single measurement location is warmer than the average temperature for a given depth and the radially opposite measurement is cooler than this same average, this would indicate that the temperature sensor with the warmer reading is closer to the pile core while the radially opposite temperature sensor is closer to the surrounding soil interface, indicating the cage is not concentric with the hole. The thermal data can reveal the cage eccentricity, the direction of cage shifting, and the loss of concrete cover outside of the reinforcing cage due to the reinforcing cage eccentricity.

Figure 2 shows a large diameter pile with 10 wires installed. The thermal data shows that wires 5, 6, and 7 are cooler than average from a depth of 3m (10 feet) through a depth of

7.25m (24 feet) while the radially opposite wires 10, 1, and 2 are warmer than the average over this same depth region. This indicates that the cage is shifted such that the region of the cage with wires 5, 6, and 7 is closer to the surrounding soils while the radially opposite portion of the reinforcing cage is closer to the pile core. The region where the cage is closer to the surrounding soils has a reduced concrete cover zone than the remainder of the pile.

The original application for the TIP method was bored piles. Quickly this method was adapted for use in CFA piles where Thermal Wires could be attached to the reinforcing cage similar to the attachment scheme used on bored piles, or it can be attached to a single center bar if this is the sole reinforcing within the pile. Next it was being used on micro piles and soil nails, and most recently it has been used extensively on rectangular panels where wires are separated by 1m and equally spaced around the reinforcing cage.

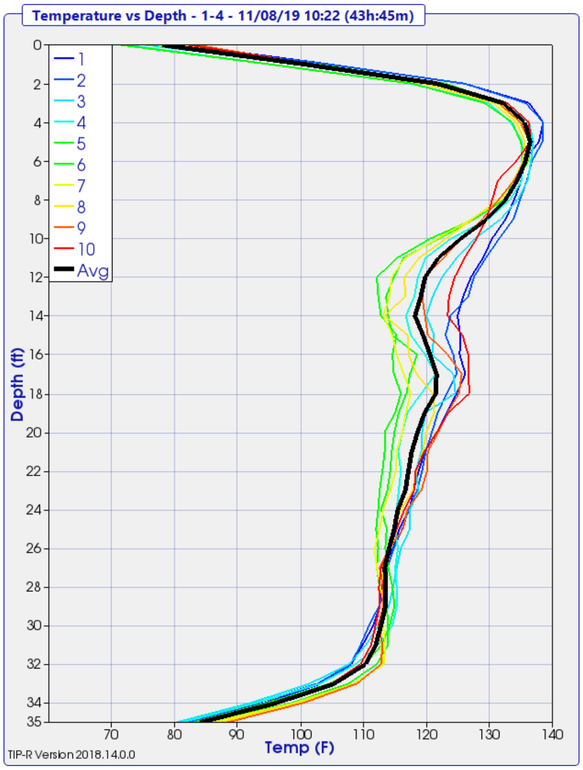


Figure 2 Cage eccentricity.

Using the total measured concrete volume, the overall average temperature is correlated to the average radius. Once this average temperature to average radius correlation has been established, the effective radius at any point along the shaft can be directly calculated. The Thermal Integrity Profiling (TIP) method can identify regions where either there is a reduction in cross-section or a reduction in concrete quality so the calculated radius is referred to as the effective radius in the pile as the temperature reduction could be due to either of these cases. The accuracy of the effective radius is directly related to the accuracy of the concrete volume measured.

## Case History

The project forms part of the largest current infrastructure undertaking in the UK, providing a High-Speed Rail Link between London and Birmingham. Long Itchington Wood Tunnel is a one-mile, twin bore tunnel, running under Long Itchington Wood in Warwickshire, UK – an ancient woodland – and is an important part of HS2’s environmental strategy to protect nature.

Figure 3. Tunnel Entrance.

Construction started with the preparation of the North Portal site ahead of the launch of the tunnel boring machine, including major earthworks and creation of the portal wall.

Once the route is built and the track and signals are in place, trains will head north from London and will leave the tunnel here before passing between Coventry and Kenilworth.

To form the tunnel entrance area, seventy-four Diaphragm Wall panels were constructed, providing 490 linear meters of wall section. A single panel was formed by two primary bites, which were then overcut and joined by a secondary bite. The wall panels were typically 1m thick and 6.7m wide, reaching depths of 21m.

The geometry and other information are shown in table 1 and figure 4. Wire configuration is shown in figure 7.

Table 1. Properties of Panel.

| Panel Nr. | Panel Dimensions (mm) | Cage Dimensions x2 (mm) | Panel Base Depth (m OD) | Cage Base Depth (m OD) |
|---|---|---|---|---|
| D006 | 6670 x 1000 | 2885 x 815 | 66.475 | 67.200 |

| Concreted Panel Length (m) | Instrumented Cage Length (m) | Theoretical Concrete Volume (m3) | Reported Concrete Volume (m3) | Overconsumption |
|---|---|---|---|---|
| 21.4 | 20.7 | 138.4 | 148.0 | 7.2% |

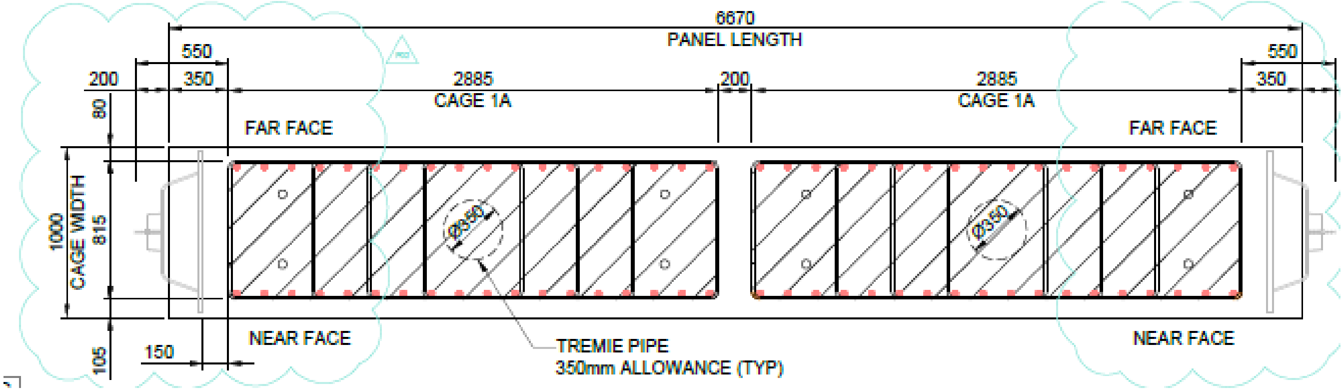


Figure 4. Panel and Cage Dimensions.

Each cage was instrumented with seven single length individual Thermal Wire cables, evenly spaced around the cage perimeter but ensuring each wire was placed with minimum likelihood of being damaged either during lifting and placement operations or by the tremie pipe insertion during the concreting process (Figure 5).

To ensure continuity and high confidence in getting data successfully, each wire was individually checked prior to installation to indicate full working order. Introducing this aspect in procedure gave all parties concerned the confidence that install was going as well as could be planned.

Figure 5. Wire placement in the cage.

A design aspect of this panel was a feature called a “box-out” section. It is essentially an area which creates no external concrete cover, so when the panel is excavated an access area is available for additional cabling/instrumentation. The feature was constructed by fixing polystyrene sheets, 2400mm long x 500mm deep x 75mm thick to the reinforcement cage. Figure 6 shows the polystyrene attachments to the reinforcing cage.

The Thermal Wire cable descriptions used in the Thermal Reporting software (TIP-R) is shown in figure 8. The complete cable description including location number, cable length, nodes above concrete, distance to reference cables, and serial numbers are included in this table and considered in the analysis.

Figure 6. Cage with foamboard attached.

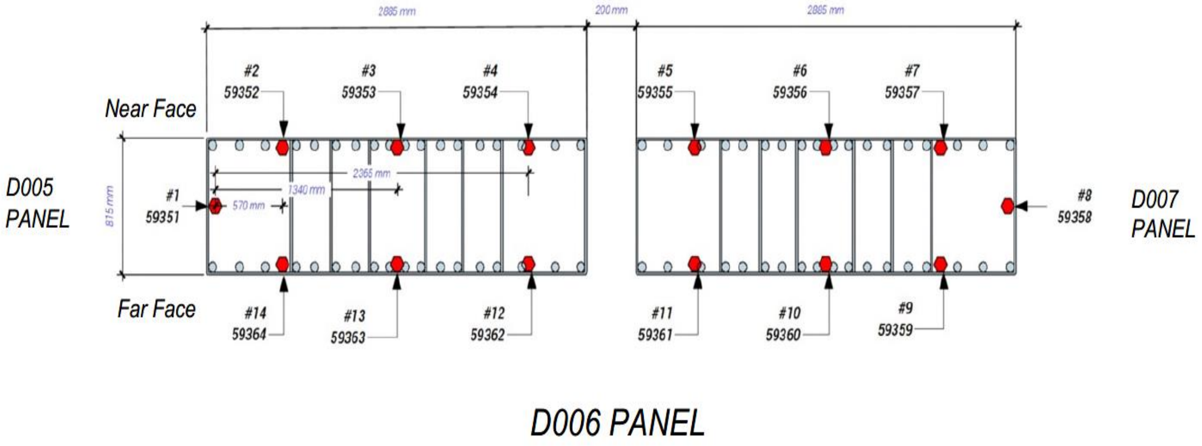
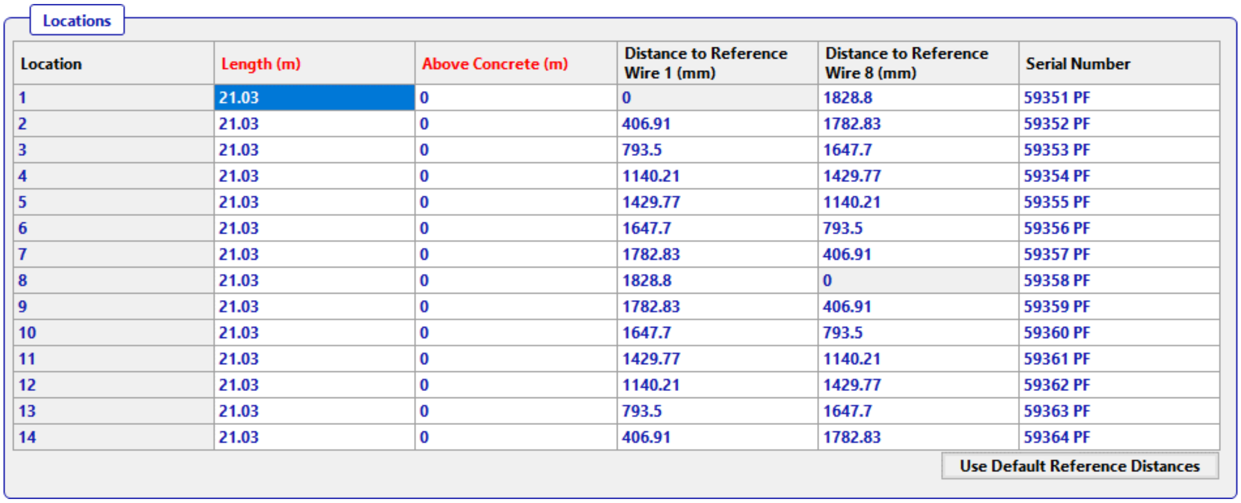


Figure 7. Thermal Wire layout in panel.



| Location | Length (m) | Above Concrete (m) | Distance to Reference Wire 1 (mm) | Distance to Reference Wire 8 (mm) | Serial Number |
|---|---|---|---|---|---|
| 1 | 21.03 | 0 | 0 | 1828.8 | 59351 PF |
| 2 | 21.03 | 0 | 406.91 | 1782.83 | 59352 PF |
| 3 | 21.03 | 0 | 793.5 | 1647.7 | 59353 PF |
| 4 | 21.03 | 0 | 1140.21 | 1429.77 | 59354 PF |
| 5 | 21.03 | 0 | 1429.77 | 1140.21 | 59355 PF |
| 6 | 21.03 | 0 | 1647.7 | 793.5 | 59356 PF |
| 7 | 21.03 | 0 | 1782.83 | 406.91 | 59357 PF |
| 8 | 21.03 | 0 | 1828.8 | 0 | 59358 PF |
| 9 | 21.03 | 0 | 1782.83 | 406.91 | 59359 PF |
| 10 | 21.03 | 0 | 1647.7 | 793.5 | 59360 PF |
| 11 | 21.03 | 0 | 1429.77 | 1140.21 | 59361 PF |
| 12 | 21.03 | 0 | 1140.21 | 1429.77 | 59362 PF |
| 13 | 21.03 | 0 | 793.5 | 1647.7 | 59363 PF |
| 14 | 21.03 | 0 | 406.91 | 1782.83 | 59364 PF |

Figure 8. Thermal Wire description and layout in TIP-R reporting software.

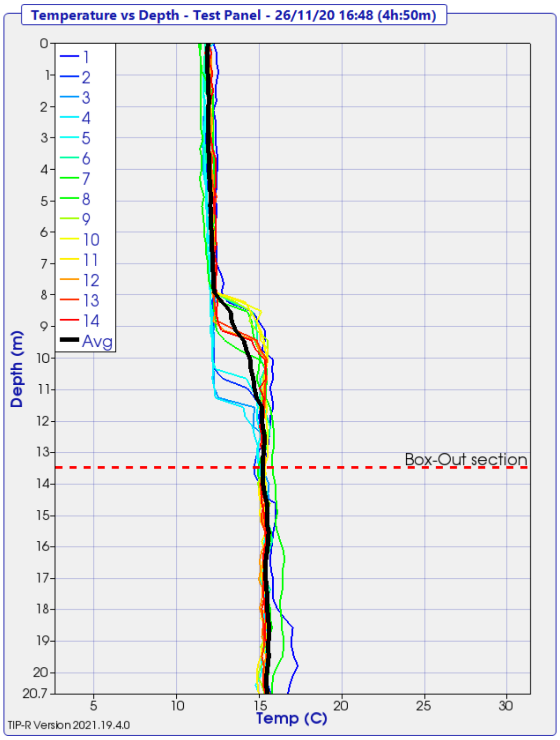


Figure 9. Thermal data during casting process.

Since monitoring begins before concrete placement this useful period allows for confirmation of concrete input and how the panel is being poured. Uneven placement could lead to unequal pressures and possible collapse of panel side walls. Concrete levels are clearly defined in Figure 9.

The optimal time for the pile profile generally occurs between one-half the time to peak temperature and the time of peak temperature. The peak temperature for this foundation type was approximately 82 hours after placement (Figure 10).

As shown in Figure 10, the average overall peak temperature recorded was 34.5$^0$C and the maximum temperature was 39.5$^0$C at the mid-point of the box-out section. Minimum temperature was 29$^0$C seen in wire #8, which consistently reported a lower peak temperature throughout and due to reduced concrete cover at this location. The reduced cover and exposure to increased supporting soil also influenced wires #7 and #9. The opposite end of the panel (wires #1, #2 and #14) was keyed into a previously completed panel so proximity to the soil was not as prominent.

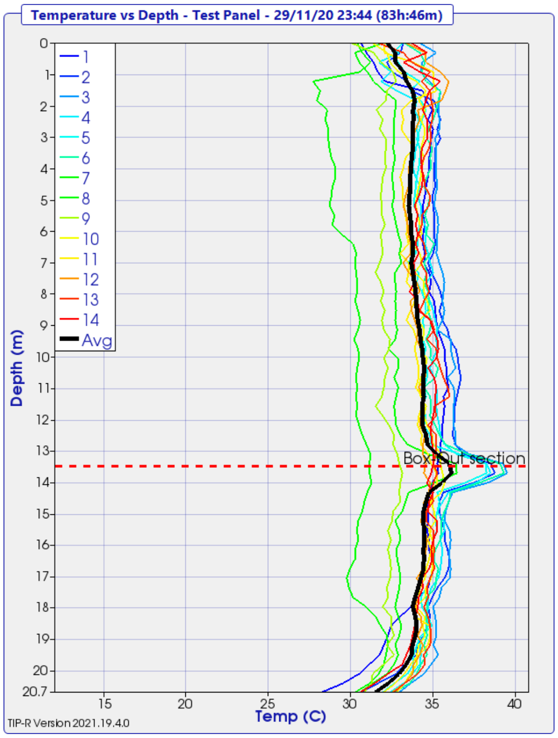


Figure 10. Thermal data at peak temperature

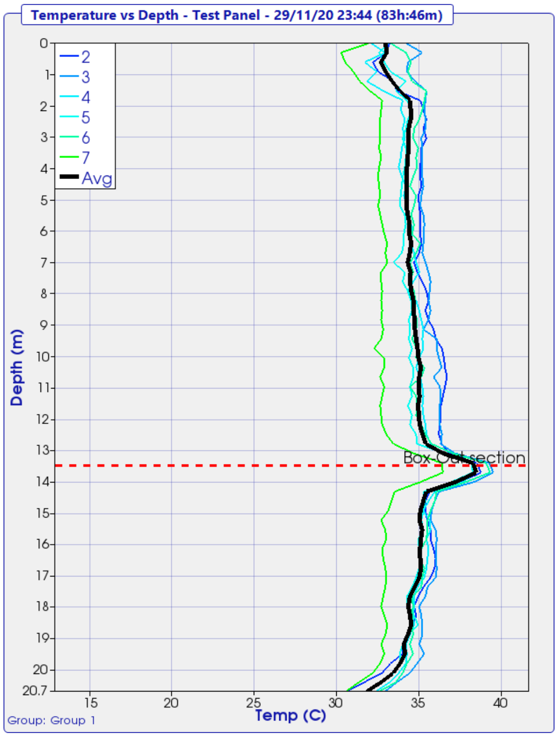


Figure 11. Thermal data showing foamboard Location.

The increase in peak temperature around 13m depth is consistent with the insertion of the polystyrene box-out panels attached to the outside of the reinforcement cages on the near face of the panel. Polystyrene acts as an insulator of heat and subsequently did not allow heat dissipation into the surrounding soil.

Variations towards the panel base were consistent and in line with current theory regarding temperature roll-off. The overall thermal signature indicated the panel was continuous with no abrupt reductions in temperature over the tested length. All fourteen wires operated sufficiently throughout the monitoring phase.

**Conclusion**

The Thermal Integrity Profiling (TIP) method can overcome many of the limitations associated with the Low Strain and cross-hole sonic logging (CSL) methods. It has many advantages including;

1. Facilitating accelerated construction,
2. The ability to evaluate the entire cross-section of the embedded foundation element, including the area outside of the reinforcing cage and over the entire length,
3. Assess piles or panels with non-uniform shapes,
4. Assess any eccentricities in the reinforcing cage,
5. Locate where an anomaly occurs within the element by depth and quadrant.

The Thermal Integrity Profiling (TIP) method is not limited in length to diameter ratio with the only limit on depth being a reinforcing cage/bar must extend to the base so the wire can also reach the base. The inherent limitations with TIP testing are the time sensitive nature of the test, as the data must be collected during the hydration process as well as the need to cast sacrificial wires into the pile. As the Thermal Integrity Profiling (TIP) method determines the effective pile radius along the entire length, designers and engineers can better assess the incorporation of shafts into the foundation where anomalies or losses of concrete cover has been detected.

The technical advantages of the Thermal Integrity Profiling (TIP) method have been clearly identified in this paper; other clear advantages are the cost savings both in material and in the installation of Thermal wires in relation to CSL. Safety of the piling crew is enhanced, particularly with sectional cages with reduced handling of joints and the cost for post grouting of tubes. Additionally, there is generally a savings in labour as the field installation of the Thermal Wire cables done by the contractors onsite and the data transmitted through the cloud to the specialist testing agency, minimizing, or eliminating the need for site visits by the specialist testing agency.

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